SNOWMELT-GENERATED RUNOFF AND SOIL EROSION IN FIFE, SCOTLAND

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ABSTRACT

The hydrology and contrasting erosional responses of two snowmelt events on arable farmland in Fife, Scotland, are compared. Snowmelt-generated runoff in January 1993 caused widespread soil erosion across eastern Scotland. Gullying was exemplified by three sites in Fife, where thaw of a drifted snowpack was augmented by rainfall to produce a larger erosive response than meteorological data alone would have predicted. Up to 127 m^3 of soil was lost from individual gullies in fields sown to winter cereals. In February 1996 snowfall of comparable depth again covered the field area, but a more uniform snowpack, slower thaw, greater crop cover and lower rainfall during the thaw phase combined to lessen the impact of erosion. These case studies demonstrate the complexity of the erosion/runoff relationship for rain on snow events, in which erosional severity depends not just on snow depth but on snow distribution, thaw rate and the amount and timing of rainfall during the thaw phase. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

Examples of water erosion of soil in the United Kingdom have been reported from central and southern England (Reed, 1979; Morgan, 1980; Evans, 1990; Colbourne and Staines, 1985; Boardman, 1993). Soil erosion in Scotland has recently received a similar degree of concern. Speirs and Frost (1985) suggest an increasing incidence of soil erosion in eastern Scotland, while others (Frost and Speirs, 1984, 1996; Duck and McManus, 1987; Kirkbride and Reeves, 1993; Davidson and Harrison, 1995) have described individual events. Erosion surveys and hazard mapping have been undertaken by Watson and Evans (1991) and Frost (1993).

These accounts establish that climate and land-use practices leave Scotland's cultivated soils vulnerable to accelerated water erosion in autumn and winter, even though Scotland is not subject to high intensity rainfall by international standards. Few studies explicitly link snowmelt with erosion on arable land in the UK, though Speirs and Frost (1985) mention that snowmelt has generated erosive runoff at some Scottish sites. Nevertheless, the importance of snowmelt-generated runoff and the effect of frozen soil is well documented in other countries. Alstrom and Bergman (1990) give examples for southern Sweden. Similar accounts exist for North America (Nicholaichuk, 1967; Burwell *et al.*, 1975; Van Vliet and Wall, 1981; Voroney *et al.*, 1981; Zuzel *et al.*, 1982; Spomer and Hjelmfelt, 1983; Kirby and Mehuys, 1987). In the UK, erosion events involving frozen conditions have not been widely reported, suggesting these are rare events, or are not frequently observed.

In January 1993, snowmelt-generated runoff initiated severe erosion on arable land and contributed to flooding across the region. Media interest surrounded blizzard and flood conditions, but erosion of farmland was also recorded and local impacts are described in this paper. In February 1996 extensive snowfalls followed by widespread thaw again produced an erosive response which was by contract less severe. This paper examines the hydrology of each event to investigate why apparently similar snowfalls produced different erosional responses. This knowledge will help identify threshold conditions for snowmelt-induced erosion which may aid hazard evaluation in the future.

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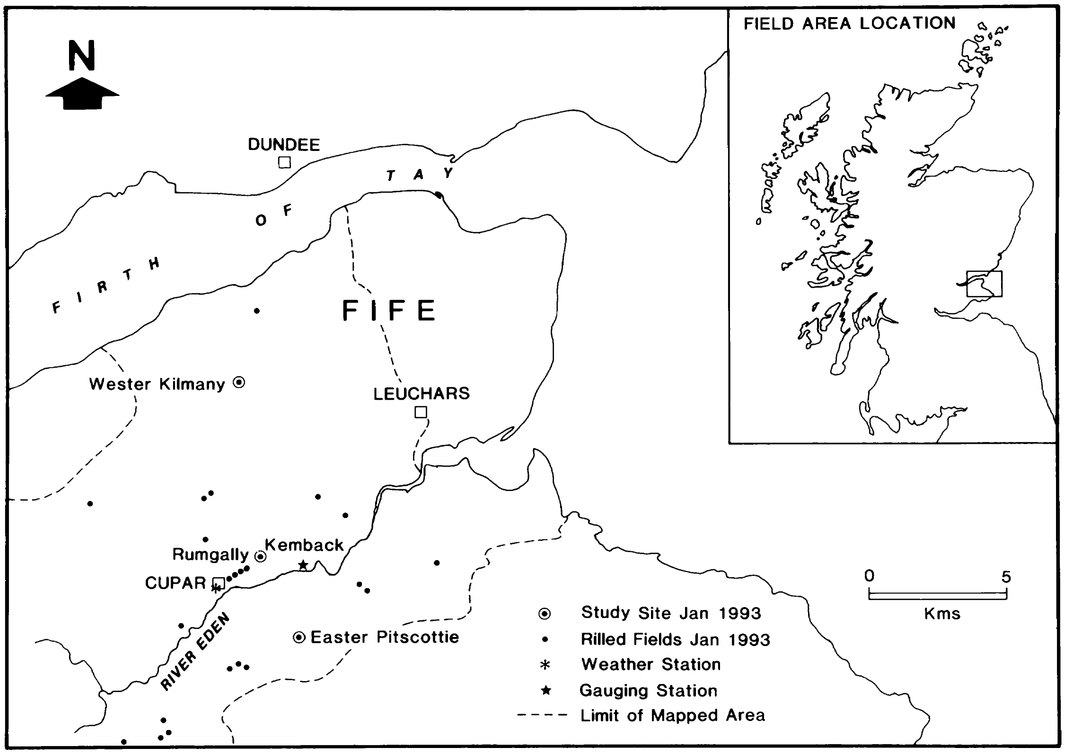

Figure 1. Map of field area, showing weather station, gauging station and location of eroded sites

THE STUDY AREA

The study area (Figure 1) consists of arable farmland on lowland undulating hills, a topographic form found by Evans (1990) to be vulnerable to erosion. Soils are light textured and stony and underlain by compact till or fluvioglacial sand and gravel below a depth of 30–50 cm. Land use in the area is intensive arable production and livestock husbandry, often creating a downslope landscape zonation from pasture or wooded hilltops with thinner soils to arable crops on midslopes and valley floors. The predominant crop types include wheat and barley (both autumn and spring sown), legumes and root crops, and oil seed rape.

SNOWMELT HYDROLOGY

Local hydrometric data allow a direct comparison to be made between the temporal distributions of snowfall, rainfall and runoff in the Cupar area (Figure 1), against which erosional impacts can be assessed.

January 1993

From 11 January 1993 a succession of Atlantic depressions brought blizzard conditions across Scotland. Snow drifted in winds gusting to 30 knots for three days (TRPB, 1993). Wind direction was predominantly WSW and brought fresh snow to Fife on four consecutive days from 11 January (Table I). The exposed centres of fields were scoured clear of snow, which drifted to depths of over 1 m in the lee of hedges and fences at field boundaries. Total snowfall on these four days was 43 cm (measured daily on a snowboard at Elmwood College, Cupar), but because the measurement was taken once daily this is a minimum value owing to melting between sampling. At Elmwood College weather station, snow cover was uneven but complete, and the snowpack compact and wet. Less than 15 minutes of sunshine was recorded on these four days (Table I). On 14 January a thaw developed with a rise in temperature to a daily maximum of 9·9°C accompanied by rain (Figure 2a). Rapid

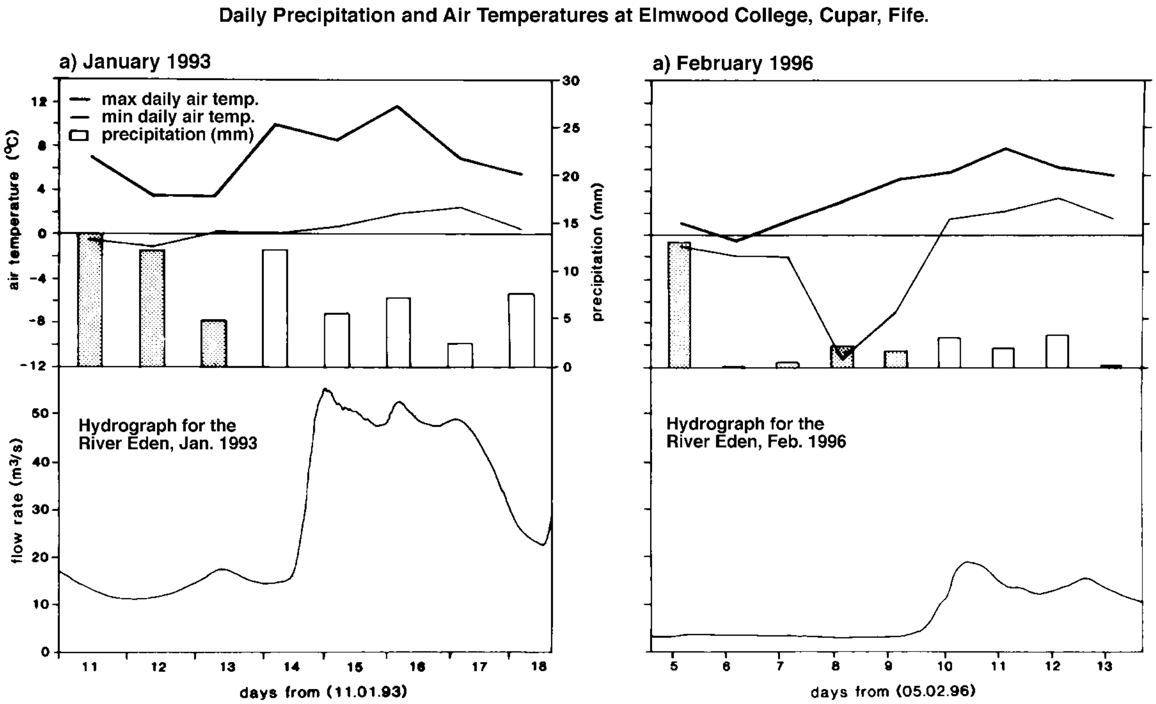

Figure 2. Hydrological information relating to snowmelt erosion events in 1993 and 1996. Precipitation and air temperatures taken at Elmwood College, Cupar, Fife, and streamflow hydrographs for the River Eden at Kemback. Precipitation falling as snow is identified by darker columns: (a) 11–18 January 1993; (b) 5–13 February 1996

Table I. Weather and climatic conditions and state of ground for both 1993 and 1996 snowmelt events. Information courtesy of Elmwood College weather station (Met. Office report station). Analysed using Metform procedure (HMSO, 1992)

Date	Wind direction	Wind speed (knots)	State of ground	Sunshine (h)	Weather (dominant type)
JAN 1993					
11/01/93	WSW	09	snow, uneven full cover	0	snow
12/01/93	WSW	19	snow, uneven full cover	0	snow
13/01/93	WSW	12	snow, uneven full cover	0	snow
14/01/93	W	19	snow, uneven full cover	0·2	snow
15/01/93	WSW	19	snow, uneven < half cover	2	sleet
16/01/93	WSW	02	snow, uneven < half cover	0	sleet
17/01/93	WSW	37	grounds surface clear	2·2	sleet and gales
18/01/93	W	09	frost on ground	1·5	not recorded
FEB 1996					
05/02/96	S	02	snow, even full cover	0	snow
06/02/96	S	05	snow, even full cover	0	snow
07/02/96	–	0	snow, even full cover	2·5	sleet
08/02/96	–	0	snow, even full cover	3·8	snow
09/02/96	W	19	snow, even full cover	0·5	snow
10/02/96	S	13	snow, < half full cover	0	sleet
11/02/96	–	0	ground surface wet	4	not recorded
12/02/96	E	5	ground surface wet	0·1	not recorded
13/02/96	SE	5	ground surface wet	5·7	not recorded

melting of the extensive saturated snowpack provided erosive runoff, augmented by 17·9 mm of rain on 14 and 15 January. Runoff response is shown by the hydrograph from the Kemback gauging station (Figure 2a). The flood peak was attained within *c*. 18 h of the beginning of the thaw. Ongoing snow accumulation and thaw associated with temperatures slightly above freezing point maintained the snowpack thickness in combination with a river discharge of 11–17·5 $m^3 s^{-1}$. The maximum hourly increase in discharge at Kemback was 6·1 $m^3 s^{-1} h^{-1}$. Extensive saturation of farmland was observed over this period.

February 1996

From 5–9 February, an extensive snowpack again accumulated across the field area, disrupting road and rail travel. On this occasion wind speeds were lower, including two days, 7 and 8 February, with no wind at all (Table I) and no significant drifting of the snowpack. The prevailing wind direction for this event was southerly until 9 February, when a 19 knot westerly wind brought a final flurry of snow to the accumulated snowpack. The total depth of snow measured on the snowboard for this period was 67 cm, that is, 24 cm more than for 11–14 January 1993. On 10 February, a maximum daily temperature increase to +5·7°C, and a minimum daily temperature rise to +1·5°C, after seven consecutive days below freezing (Figure 2b) again produced snowmelt runoff accompanied by rainfall. For this event, there was considerably less rain falling on the snowpack and at cooler temperatures than for the 1993 event. Almost 7 h of sunshine was recorded in the three days before the thaw (Table I). Runoff response, shown for Kemback (Figure 2b), shows the flood peak to be attained with *c*. 21 h of the start of the thaw, following several days of low flows of *c* 3 $m^3 s^{-1}$. The maximum hourly increase in discharge at Kemback was 1·7 $m^3 s^{-1} h^{-1}$. This rate is almost four times less than for 1993.

EXTENT OF EROSION

January 1993

In January 1993, three examples of gullying were studied on arable fields at three farms subsequent to the thaw, namely Rumgally Mains (NO 4014), Easter Pitscottie (NO 4113) and Wester Kilmany (NO 3821). Other examples were mapped in the area (Figure 1). Total soil loss from these three sites was estimated from measured cross-sections at 10 m intervals down the slope. Channel width, maximum depth and average depth of the channel were measured to estimate the total quantity of soil lost from the gullies. A total of 214 m^3 of soil was removed from the three main gullies, excluding small feeder rills, of which 127 m^3 was lost from one channel in a field at Rumgally Mains. The topography of all three fields is convex–concave in form with maximum slope angles (measured by abney level) of 8·3° to 10·0° (Table II). All fields were drilled up- and downslope and seeded to winter cereals. Sediment yields have been calculated for the drainage catchment relating to each channel, rather than for field size, because runoff was introduced into the top of the field at Easter Pitscottie.

The distribution of erosion along each thalweg is explained by the influence of the overall profile of the slope and the introduction of runoff at the top of the slope. At Rumgally Mains and Wester Kilmany farms, the gullies were fed by deep snowdrifts against field boundaries which, together with natural flow convergence, produced runoff following the fall line of the slope. At Easter Pitscottie a double gully was initiated at a fieldgate at the top of the field. Snow drifted against the upper side of the fence fed runoff through the fieldgate thus initiating the channel, with gentler fields upslope contributing to the flow. Chute–plunge pool sequences formed in all gullies but most notably at Rumgally Mains. Here, incision of pools reached depths of 1·6 m. This was accentuated by a ploughpan below the Ap horizon overlying erodible sandy soil. Most soil was lost from the midslope section of

Table II. Field slope and channel characteristics for three snowmelt-generated gullies in Fife, Scotland, January 1993. Sediment yield is not calculated based on field boundaries but on catchment drainage

Site*	Field slope max. angle (°)	Field slope mean angle (°)	Channel length (m)	Soil loss (m^3)	Sediment yield ($t\,ha^{-1}$)
RM	8·3	7·1	350	127	12·7
EP	10·0	5·7	230	76	10·1
WK	9·5	7·2	170	12	0·8

* RM, Rumgally Mains; EP, Easter Pitscottie; WK, Wester Kilmany

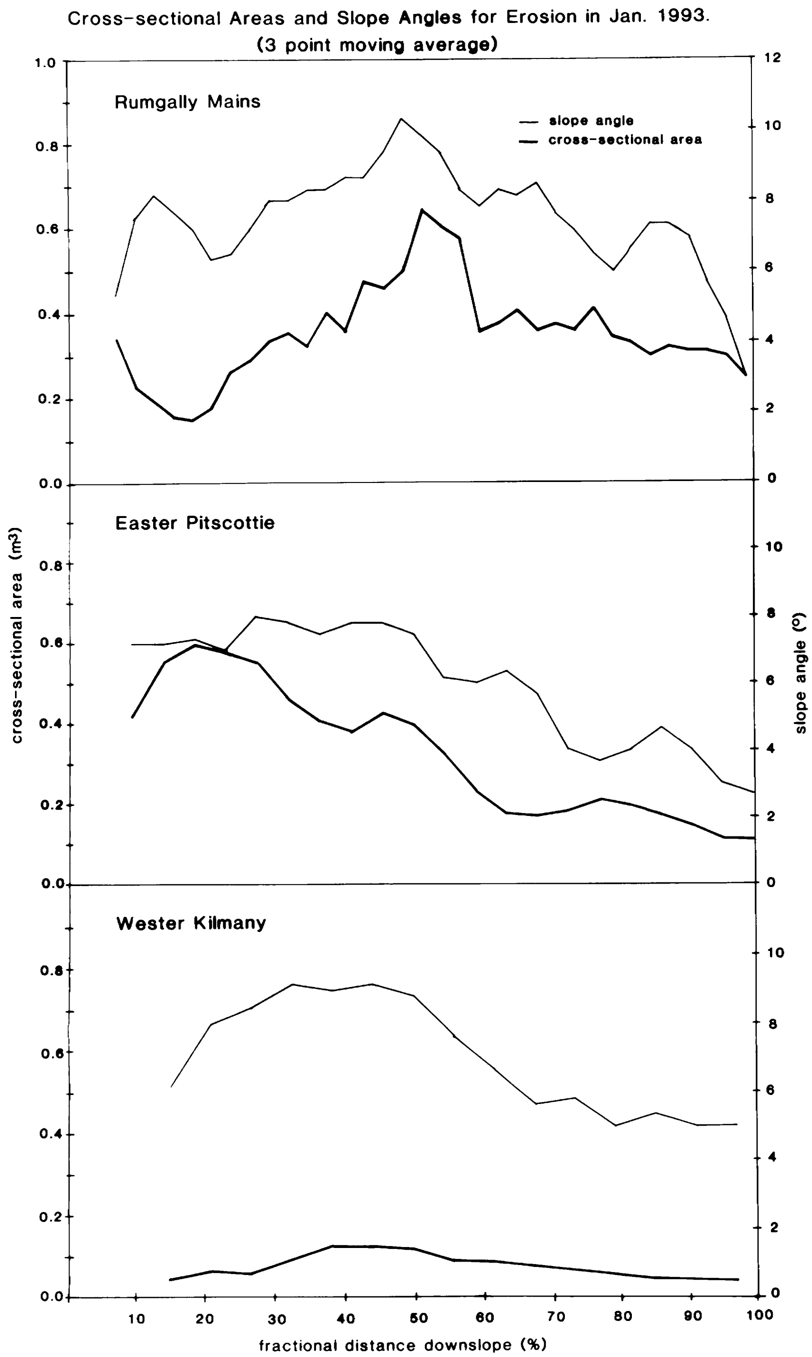

Figure 3. Field gradients and cross-sectional areas of gullies eroded in January 1993, showing distribution of soil loss down eroded channels

the three channels (Figure 3) with the larger scours eroded to over 1 m deep at Rumgally Mains. Morphological effects at this scale are probably due to obstructions such as boulders, or to natural flow instabilities. For several hours on 14 January 1993, workmen were continuously clearing the A92 Cupar–St Andrews road of soil as it washed out of the field. Such was the scale of the incision that the gully was eventually filled with aggregate by the farmer in November 1993.

The distribution of soil loss downslope (Figure 3) shows that where runoff was generated mainly within the field, the location of greatest thalweg incision corresponds to the steepest slope facets. This is in accord with other empirical evidence of maximum erosion on steepest slopes (Govers *et al*., 1996). Conversely, at Easter Pitscottie, where runoff was introduced at the upper field boundary, thalweg incision is greatest in the upper gully reach irrespective of slope. The relatively uniform gully dimensions at Wester Kilmany will also reflect the confluence of feeder rills along much of the thalweg length. In all cases, maximum cross-sectional area values are associated with chute–pool morphology and deepest incision.

Rills were predominantly aligned by the direction of cultivation and were more severe in the compacted tractor wheelings, but followed fall lines on steeper slope segments. Direction of slope can generally only deflect flow from a drill line or wheeling when the slope is sufficiently steep or the flow sufficiently powerful.

February 1996

In February 1996 only small rills were observed on bare soil fields subsequent to the thaw. Two such rills were observed at Easter Pitscottie in the same field which experienced severe gullying in 1993. Here, rills followed downslope drill lines and total soil was estimated at *c*. 5 m^3, less than 7 per cent of the total estimated loss experienced in the 1993 event (Table II). ‘Trace’ erosion, i.e. areas of surface wash but without rills, was also evident at the base of wheelings across the whole field. The other fields for which erosion in 1993 has been described in this paper were only affected to the extent that ‘trace’ erosion was visible. Notably, the ‘scars’ from the 1993 eroded channels were still visible on those fields three years later.

Many small rills were formed on other cereal fields and particularly in compacted wheelings (tramlines); surface wash was also evident but no larger channels were noted and erosion overall was volumetrically very minor.

DISCUSSION

The findings of this study show that the two rain-on-snow events resulted in markedly different erosional responses, from the locally severe rilling and gullying of January 1993 to negligible soil loss in 1996. Even though the process of runoff generation and the amount of snowmelt involved were superficially similar, information on snow depth alone appears to be insufficient for prediction of erosional response. Hydrological information (Figure 2) allows important differences between events to be identified, and the nature of the erosion threshold to be elucidated.

Potential influences on the amount and rate of runoff from snowmelt fall into three groups (Table III). The number of possible influences and the complexity of their interactions limit deterministic assessments of runoff generation and soil erosion. Nevertheless, sufficient data exist for the study events that a first attempt can be made to explain their differing erosional responses. Explanation is sought primarily for why erosion occurred at all, and secondarily for the distribution of soil loss along the line of an individual thalweg.

Snowpack properties were similar immediately prior to both events. Available data indicate approximately similar mean snow depths, and compact wet snow at or close to melting point. The one significant difference was the degree of drifting in 1993 compared to the relatively uniform snow depth in 1996. Deep drifts represent localized moisture reservoirs at which the runoff generation potential is increased above that of a uniform snow cover. Thus, erosion potential is correspondingly localized but impact intensified downslope of deep drifts. Drifts upslope of topographic hollows where flow is concentrated, as at the Rumgally site, have particular erosive potential. Snowmelt conditions during each event also show differences which may be related to erosive impact. The significant parameter is the *rate* of runoff generation, given that the erosivity of runoff will increase with the rapidity of thaw. Both events experienced similar wind speeds and air humidity, but differed in the nature and rate of temperature increase and in the amount of precipitation associated with the rise in temperature. Together, these factors suggest more rapid heat transfer and thaw of the snowpack in 1993 than in 1996. Thaw in January 1993 was a result of a rise in daily maximum temperature from +3·4°C on 13 to +9·9°C on 14 January, while minimum temperatures remained close to freezing point. Warming in 1996 involved a slower increase in maximum temperatures but a dramatic increase in minimum temperatures from −7°C on 9 to +1·5°C on 10 February. The greater increase in above-freezing temperatures in 1993, giving a greater diurnal

Table III. Influences on the amount and rate of runoff generation from a melting snowpack

Property	Significance
Snow pack properties	
Area-averaged depth	Measure of regional water-equivalent reservoir
Drift thickness	In combination, enhance local maximum runoff
Drift volume	
Drift location	
Snow density	Determine albedo and moisture percolation, hence melt factor
Snow permeability	
Snow texture	
Thaw climate	
Air temperature	In combination, determine rate of heat transfer and ablation
Humidity	
Wind speed	
Insolation	
Sub-snow soil condition	
Temperature	Erodibility reduced while frozen but enhanced during thaw
Soil moisture	Infiltration reduced by saturation, especially if frozen
Crop cover	Greater cover reduces erodibility
Texture	Influences cohesion and erodibility
Organic content	

range, can be argued to have caused more damage to the snowpack than the modest increase in daytime temperatures and reduced diurnal range in 1996. Furthermore, the temperature regime throughout each event, when compared with the maintenance of similar average snow depths, suggests that the snow depth in 1993 was the net balance between ongoing wet-snow accumulation and thawing throughout the days prior to major thaw. Meltwater percolation led to saturation of the soil during the period of snow lie. In contrast, snow accumulation and thaw in 1996 occurred at discrete times separated by a five-day lag in which dry, freezing conditions prevailed. These contrasts are reflected in the base flows of the River Eden prior in the major thaws (Figure 2). Discharges of 11–17·5 $m^3 s^{-1}$ between 11 and 15 January 1993 contrast with a flow of only 3 $m^3 s^{-1}$ between 5 and 9 February 1996.

The amount of rain falling on melting snow has two effects: it generates runoff directly, and supplies heat for snowmelt to augment direct runoff. Furthermore, Zuzel *et al*. (1982) calculated dew point for rain falling on snow in Oregon and suggested that the latent heat of water vaporization provides energy, when the dew point of the overlying air exceeds 0°C, to greatly accelerate the rate of snowmelt and runoff. They found that condensation melt accounted for as much as 38 per cent of the total hourly melt. The major thaw days in 1993 and 1996 experienced rainfall of 12·3 mm and 3·1 mm, respectively. Though the erosive event received about four times the rainfall of the non-erosive event, these totals in themselves are below the daily rainfall generally regarded as the minimum for erosive runoff in the region. For example, Speirs and Frost (1985) found empirical evidence that 15–20 mm of rainfall over 24 h was required to initiate erosion. The effect on the rate of runoff generation, acting through increased rate of snowmelt, was more significant. If one assumes that the temperature of falling rain was equal to that of the surrounding air, it can be estimated that 12·3 mm of rain at *c*. 5·0°C (14 January 1993) would have contributed eight times as much heat energy for snowmelt as 3·1 mm of rain at *c*. 2·5°C (10 February 1996).

Inference of the extent to which soil antecedent conditions affected erosion in the two study events is necessarily limited by lack of data. In areas of transient snow cover, and when warm spells repeatedly interrupt a cold winter, soil macropores may be filled with ice when infiltrating water freezes and this will reduce the rate of infiltration and encourage surface runoff. Furthermore, the erodibility of soil particles is increased due to prior freeze-drying, which reduces particle aggregation. If runoff is discharged when the soil surface is concretic (impermeable because of soil frost), or frozen just below the surface, overland flow may be established very quickly. On recently seeded winter cereal crops there will be few barriers to flow as soil is

prepared to a fine tilth for planting. The flow will generally form anastomosing courses with no pronounced channels. In this situation gully erosion would be unlikely, but a considerable amount of topsoil may be lost from a relatively large amount of the field surface area. Loss of seedlings and nutrients provided for those crops is likely especially if such an event occurs before the crop cover and rooting depth are sufficiently established. Runoff over frozen soil has been observed several times in the Fife field area, but lack of data referring to the soil horizon temperatures for the events in January 1993 and February 1996 make it difficult to know exactly the extent to which the soil was frozen on these occasions. Grass temperatures at Elmwood College were <0°C beneath the snowpack from 11–14 January 1993, suggesting that frozen soil and reduced infiltration are likely to have been widespread during the 1993 event. No data are available for February 1996. Soil was observed to be heavily saturated in the 1993 event but probably below saturation point in 1996.

Returning to the question of why the January 1993 event caused rill and gully development but the February 1996 event did not, these results demonstrate that erosion impact was dependent on circumstances acting in combination rather than on any one dominant influence. Both meteorological and soil factors in the days prior to the major thaw were as significant as those on the day itself. The critical factors seem to have been the rate of runoff generation and the concentration of this runoff. In January 1993 this was very rapid as the stream hydrograph (Figure 2) indicates clearly. The reasons were fourfold: the snowpack was drifted and potential moisture sources thereby localized and concentrated; thaw was rapid due to a sharp rise in daytime temperatures; rainfall during thaw, though modest in amount, caused rapid melting by reason of its warm temperature; and the soil surface was preconditioned for erosion due to minimal crop cover and saturation by slow thaw over previous days. In February 1996, by contrast, snowpack was not drifted, thaw followed dry frozen conditions and was slower due to less sensible heat input from rain and to only a modest rise in daytime temperatures. Speirs and Frost (1985) have recorded erosion events with similar conditions, in 1982 and 1985, where rainfalls of ≤10 mm were sufficient to initiate erosion on snowpacks of 200 and 150 mm depth, respectively.

Assessment of erosion hazard involves not just the identification of conditions causing erosion, but may be extended to examine the distribution of soil loss along flowlines within fields. Gully morphometry (Figure 3) contrasts one field (Easter Pitscottie), where runoff was introduced from upslope into the top of a convex–concave field, with the other two where runoff was entirely generated from snowdrifts within each field (Rumgally Mains and Wester Kilmany). In the latter cases, there is a close relationship between the gully cross-section and slope angle, as predicted by other authors (e.g. Govers *et al*., 1996). In the former case, gully dimensions adjust to slope angle only on the lower slope. Maximum gully dimension is attained very early, at the slope top, as 'underloaded' runoff scours immediately on entry to the field. By implication, steeper slope segments within the landscape can be expected to yield most soil only under conditions of within-field runoff generation. A more complex pattern develops on long slopes containing several fields with attendant drainage management problems, so that the loci of maximum soil losses may show no simple relationship with topography. This will especially be the case when runoff is introduced from upslope low-infiltration surfaces such as pasture and farm tracks.

Snowmelt is rarely included in predictive modelling packages or in predictive equations such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its successors. The basic equation for the USLE has been refined, however, to include the ability to handle snowmelt. In addition, The Guelph model for evaluating the effects of Agricultural Management systems on Erosion and Sedimentation (GAMES) (Dickinson and Rudra, 1990) can also incorporate a snowmelt component. Both of these models use the USLE as their basic driving equation and there are limitations on their ability to translate to the European agricultural environment, and indeed from the plot scale to process-based investigations at the field scale. The main consideration when incorporating snowmelt into such models is that lag-time between precipitation falling and snow thawing may be considerable. Therefore it is imperative to consider the effects on runoff generation of soil and air temperatures for erosion-prone sites in the days preceding, as well as including, major thaw events.

CONCLUSIONS

Snowmelt-generated soil erosion was observed to be widespread in Fife during January 1993. The erosional

response of the snowmelt runoff was locally very severe and proved more serious than the precipitation record alone would have indicated. The erosional response was mainly gully formation on sloping arable land planted to winter cereals, following rapid thaw of a heavily drifted snowpack on frozen soil. In February 1996 the snowmelt response was less severe even though the average snowpack thickness was greater at any one time. A more even distribution of snow, less rain falling at cooler temperature onto the snowpack, drier antecedent soil moisture conditions, and a more established crop cover combined to lessen the potential for severe erosion on this occasion.

The spatial distribution of rilling may be different for a snowmelt-generated event than for summertime or other waterborne erosion events because the snow has a distribution dependent on wind transport and drifting. The local intensity of erosion is enhanced during snowmelt because the snow 'reservoir' contributes considerable runoff. If snow is in thick drifts rather than an even sheet, as in 1996, runoff is initiated from a concentrated source rather than adding uniformly to overland flow.

The implications for hazard prediction are considerable. When runoff is disproportionate to the rainfall total on the thaw day, other climatic variables must be considered. Relevant factors include maximum daily air temperatures, hours of sunshine and snow depth on the ground, both during the days preceding and including major thaw events. Inclusion of more data will make analysis of erosion events a more complex task, but will help to explain anomalies created by events such as January 1993 and February 1996.

In terms of probability modelling it is difficult to account for all the variables influencing a single event. Erosional response will vary from site to site depending on the individual site characteristics. Therefore, while prediction from meteorological data may provide an estimation of hazard at a regional scale, erosion control procedures would have to be based on local knowledge of erosion-prone fields. Maximum soil losses are systematically related to topography only when runoff is generated in the same field. Erosion by runoff introduced to fields from upslope would depend on the local distribution of tracks, drains and field boundaries. Erosion control procedures intended for summer soil loss may not be appropriate in areas where winter soil loss predominates, especially in areas prone to transient snow cover, drifting, and frozen soil.

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